APPLE

Adaptive Photonic Phase Locked Elements

- An Overview -

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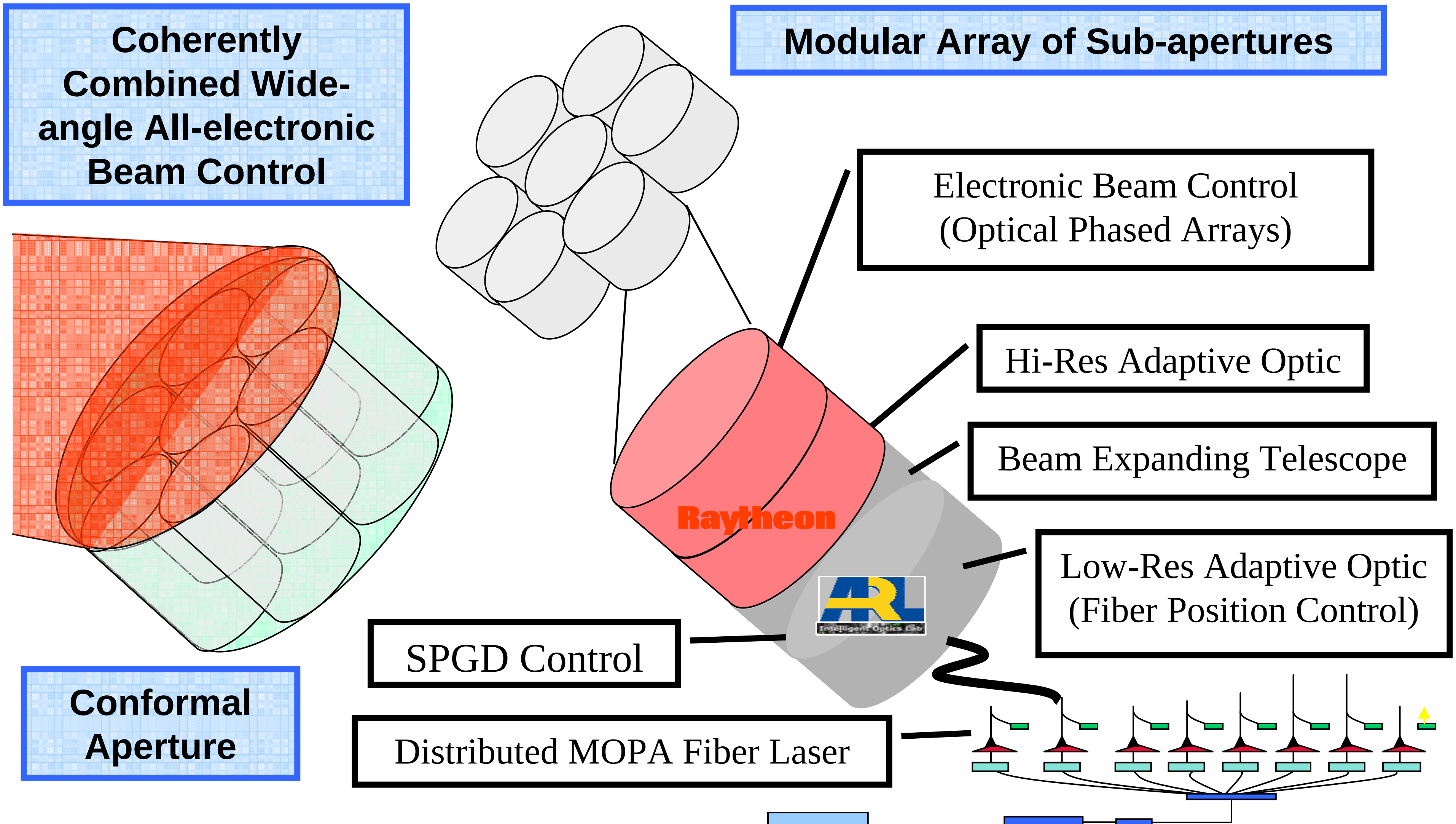
APPLE Vision:
Multi-function EO Sensor/Weapons Beam Control

APPLE Scenario

APPLE Architecture
- A Phased Array of Phased Arrays -



OPA: An Optical Analog of Microwave Phased Arrays

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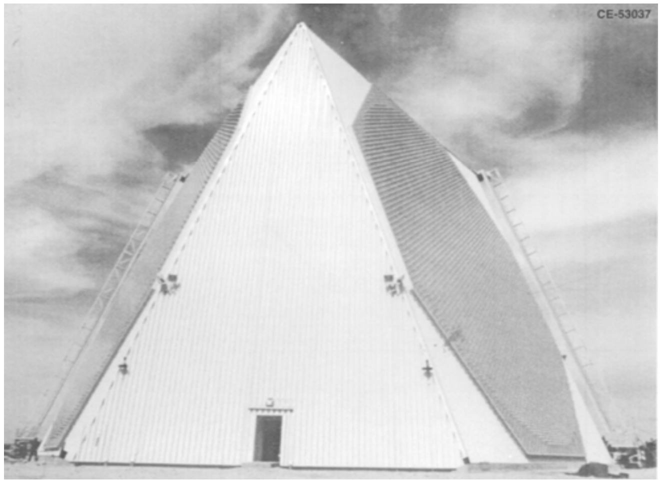
Brings to EO systems the enhanced functionality & mission flexibility that microwave phased arrays brought to RF systems

PAVE PAWS
Phased Array Radar



7,000 Phase Shifters, 35 Foot Array

- **Beam Steering**
- **Multiple-beam Generation**
- **Electronic Focus**

Optical Phased Array (OPA)

10,000 Phase Shifters, 4 cm Array

Optical Phased Arrays

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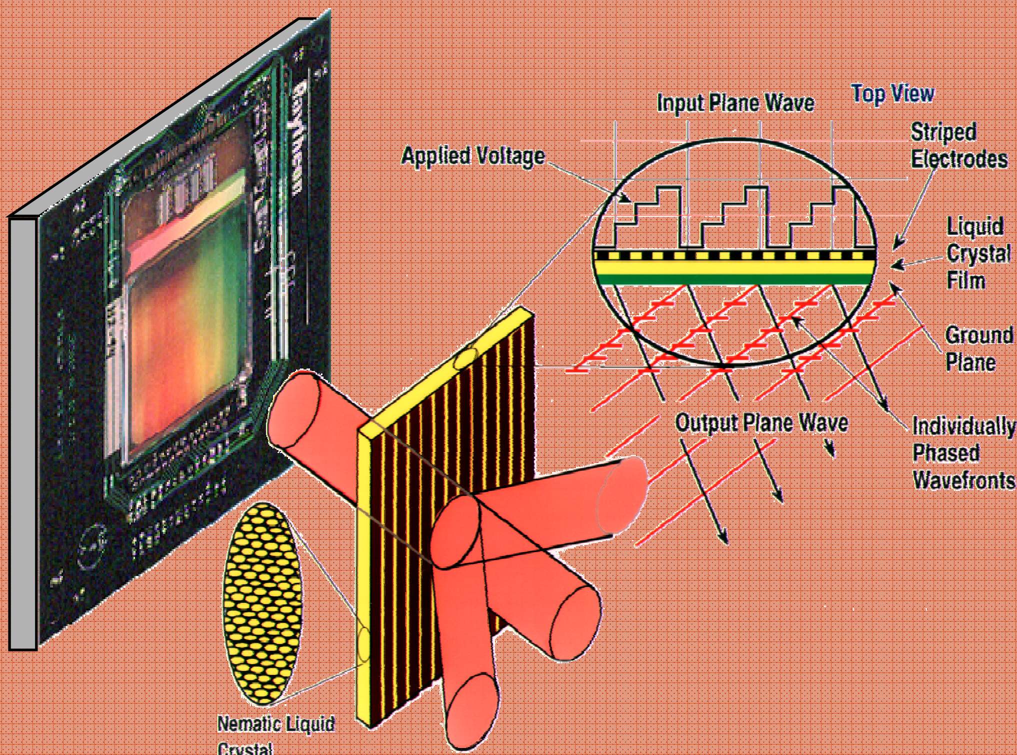
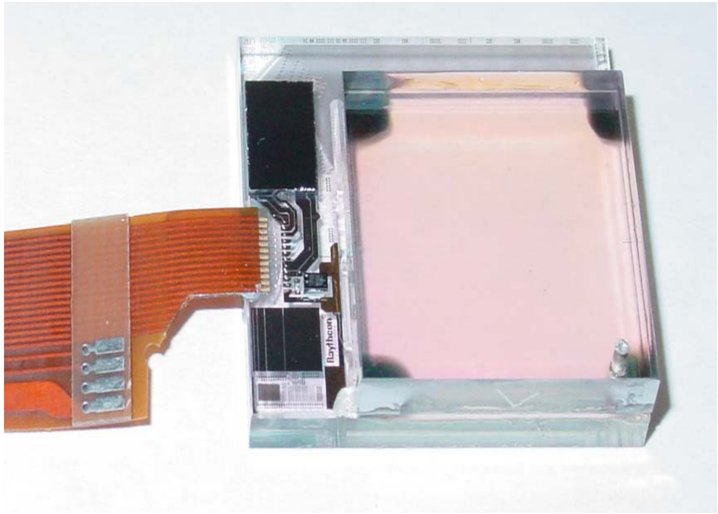
How Does an Optical Phased Array Work?



- **Raytheon invented and developed the OPA to give electro-optic sensors the advantages of phased array antennas**
  - The OPA modifies the phase front across an aperture through photo-lithographically patterned liquid crystal phase shifters
  - Cascaded orthogonal cells provide azimuth and elevation steering
- **An OPA is the optical analog of a microwave phased array antenna. It controls laser beams electronically.**
  - Non-mechanical beam control has been the "holy grail" of optical beam steering
  - Optical wavelengths are 10,000 × smaller than RF; OPA's are 10,000 times smaller than microwave arrays
  - A Pave Paws antenna with the angular accuracy equivalent to an OPA would have to be 20 miles in diameter

High-Precision Beam Control Demonstration

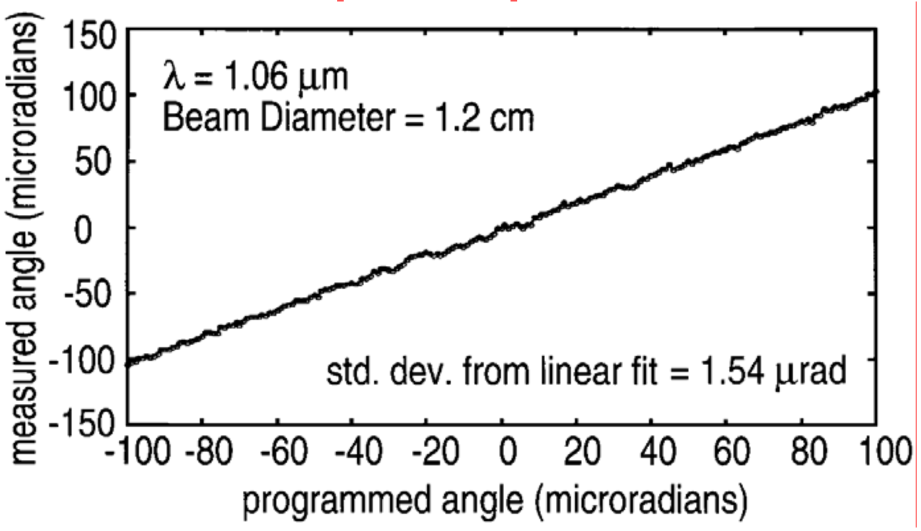
Optical Phased Array



Conditions:

- **Wavelength: 1.06 microns**
- **Beam diameter ($1/e^2$): 1.2 cm**
- **Far-field spot size: 105 μrad**
- **Angular position determined by centroiding beam spot on a FPA**

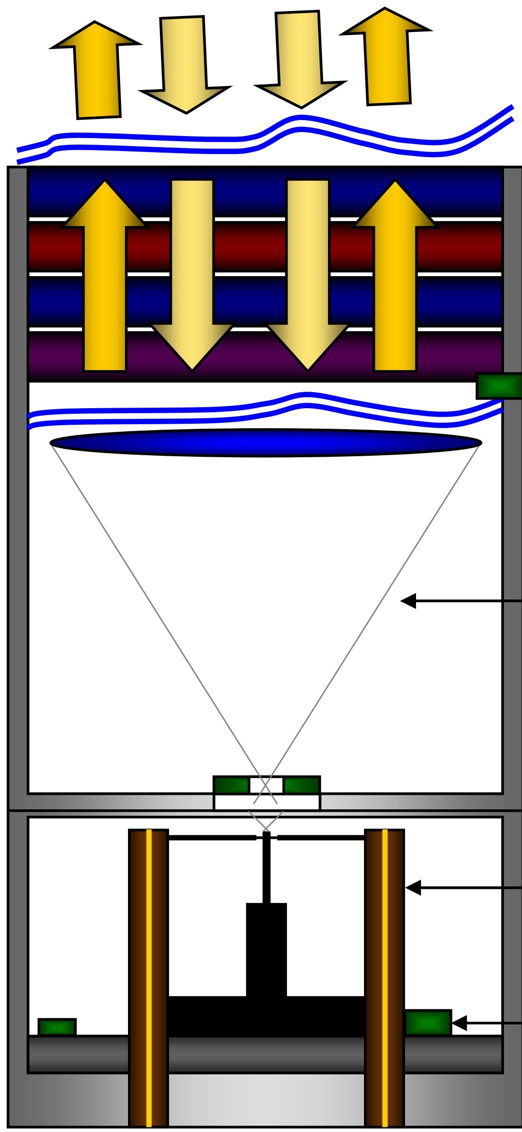
Open-loop Data



Results:

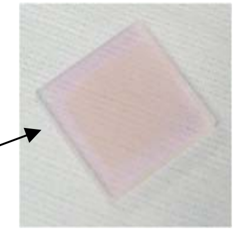
- **1.5 μrad rms noise on otherwise strictly linear, open-loop response**
- **Smallest detectable motions correspond to 1.5% of far-field spot size**
- **RF rule of thumb is $1/100^{th}$ spot motions**
- **Data are actually limited by system vibrations**

Aperture Module



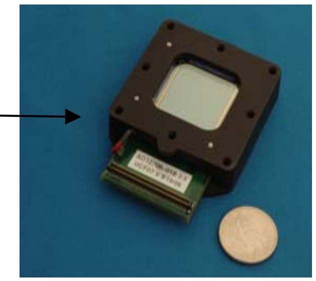
Zone-fill OPAs

PTRG Holographic Gratings



Zone-select OPAs

Adaptive Optic



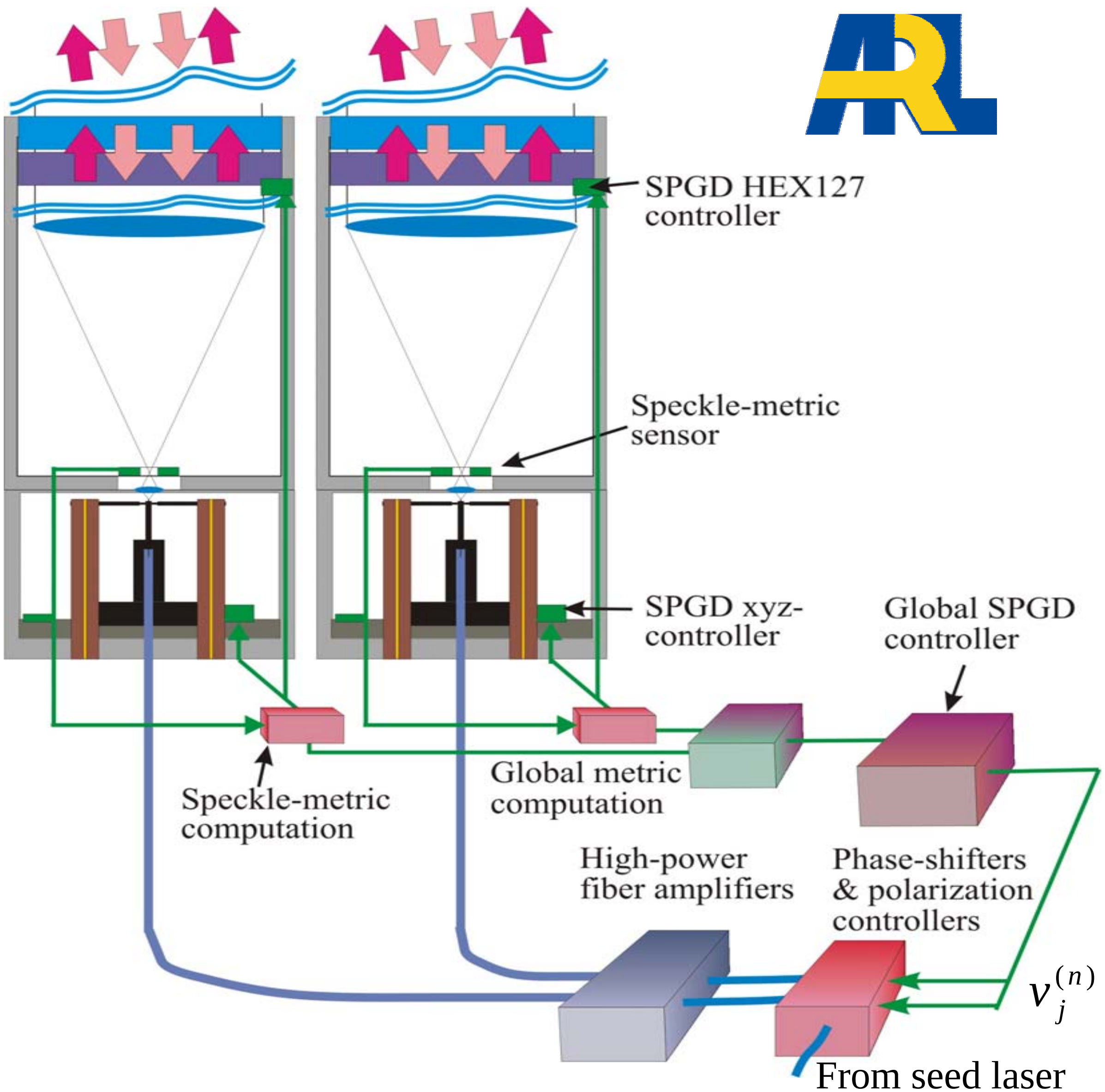
SPGD AO Controller

Beam Expander

Fiber-Tip XYZ-Actuators

XYZ control via Stochastic Parallel Gradient Descent (SPGD) algorithms

APPLE: Control Concept



APPLE Transceiver operation with a non-cooperative target

Directed energy applications

Global metric: Speckle-metric

$$J_{ph} = \sum_{j=1}^{M} J_j$$

Phase-locking algorithm

$$v_j^{(n+1)} = v_j^{(n)} + \gamma \tilde{J}_j^{(n)}$$

Local metric: Local speckle-metric

$$J_j$$

Aberration compensation algorithm

$$u_j^{(n+1)} = u_j^{(n)} + \gamma \delta u_j^{(n)} \delta J_j^{(n)}$$

Componentry Developed

Raytheon

Component	Developer	Special Capabilities
Spatial Phase Modulator for Adaptive Optics	Raytheon	127 Pixels in Transmission-mode format 500 Hz Frame Rate High power capability (kW class)

APPLE Componentry

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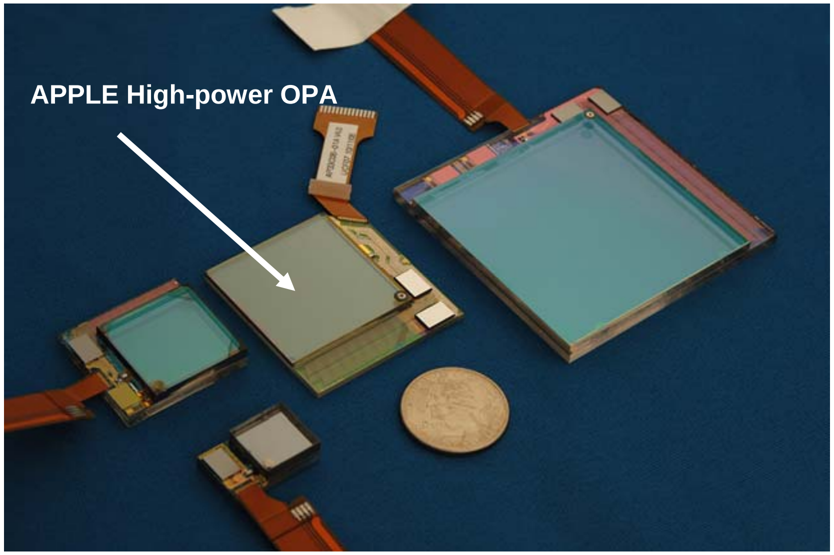
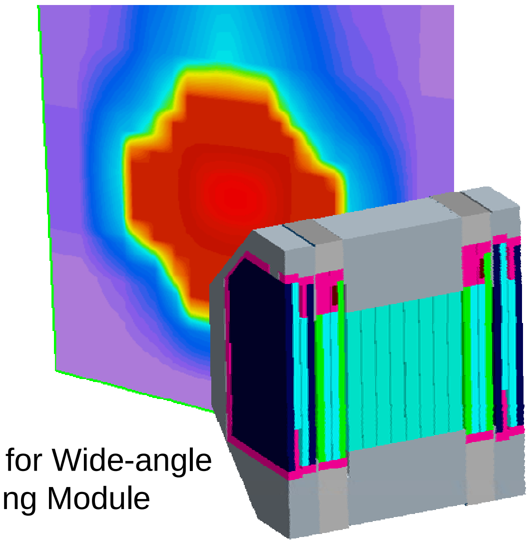
Large-aperture Optical Phased Arrays



Aperture Thermal Model at 1 kW

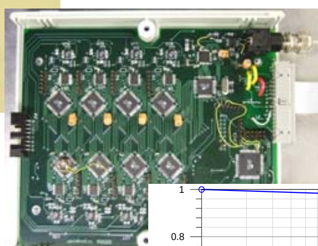
Demonstrates acceptable temperatures and gradients for Phase 1 components

Prototype OPA's Tested to 113 W



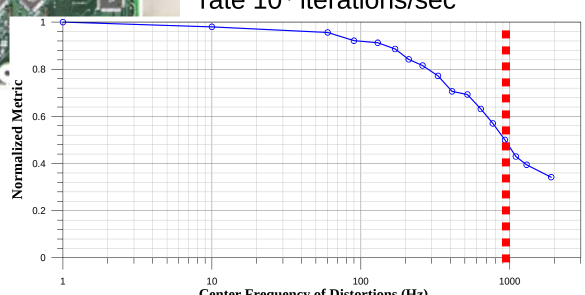
Package Design for Wide-angle Beam Steering Module

20 kHz closed-loop Phase-locking demonstration (7 channels)

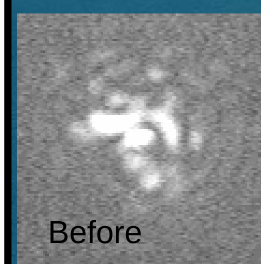


Electronics
Phase-locking SPGD micro-processor; update rate 10^4 iterations/sec

Components Development
Fiber-tip tip/tilt actuators:
100 µm amplitude,
3 kHz bandwidth



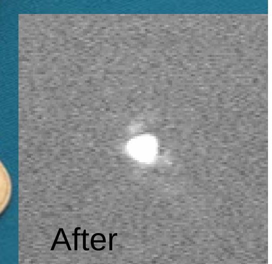
Adaptive Optic Spatial Phase Modulator



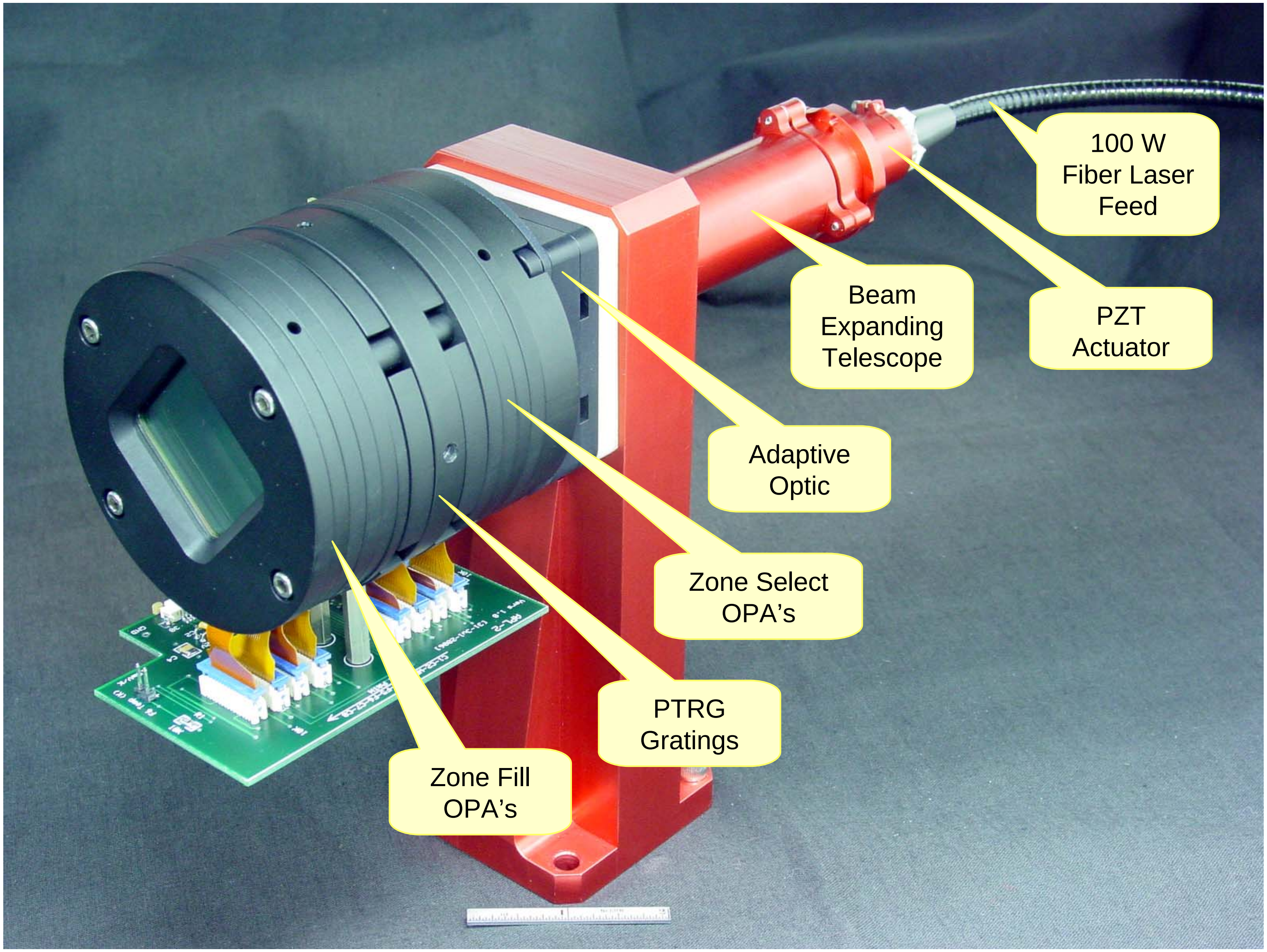
127 Pixels

kW Class

300 Hz Frame Rate

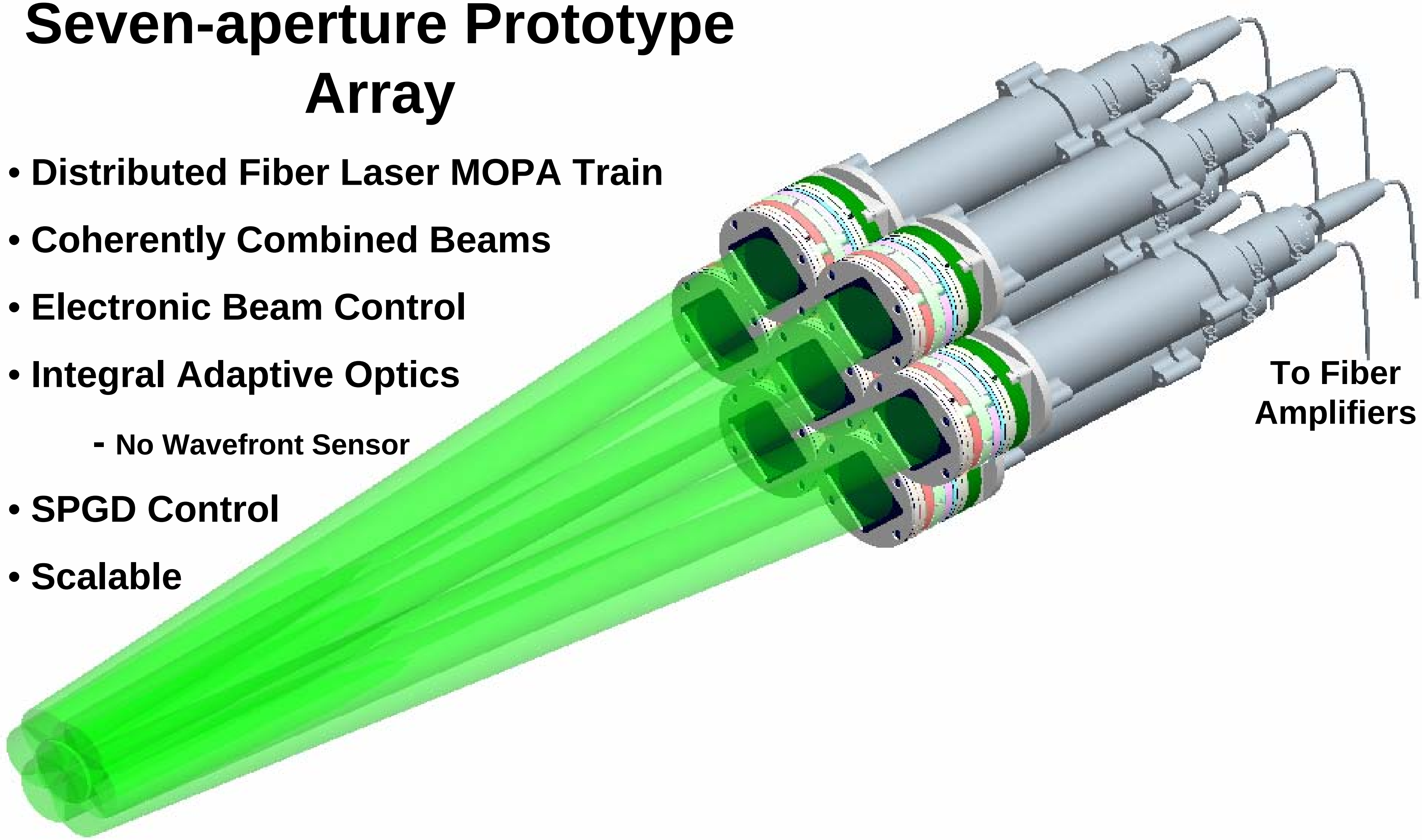


APPLE Prototype Aperture



Seven-aperture Prototype Array

- Distributed Fiber Laser MOPA Train
- Coherently Combined Beams
- Electronic Beam Control
- Integral Adaptive Optics
  - No Wavefront Sensor
- SPGD Control
- Scalable



APPLE: Beam Control for the 21st Century

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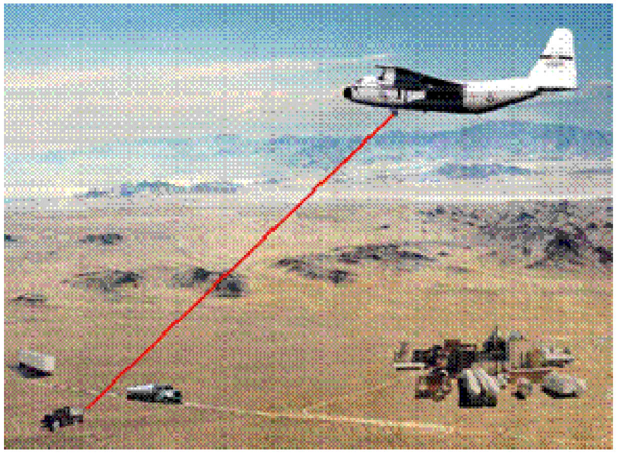
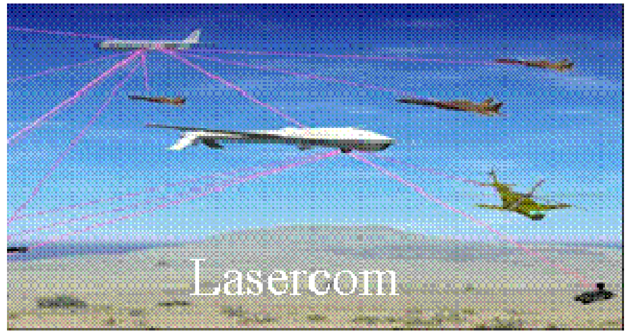
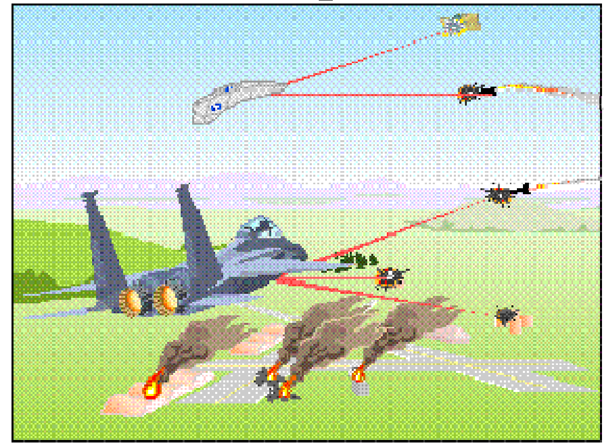
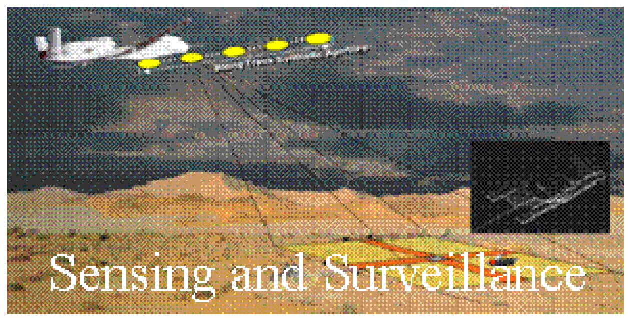
ATL



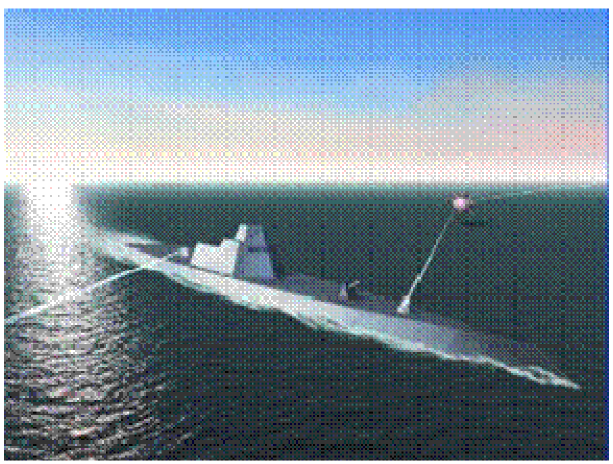


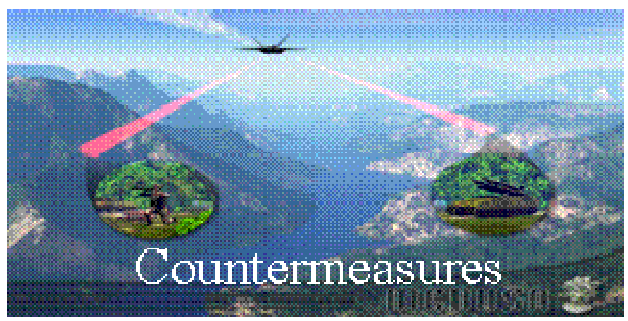
HEL Fighter





Naval HEL



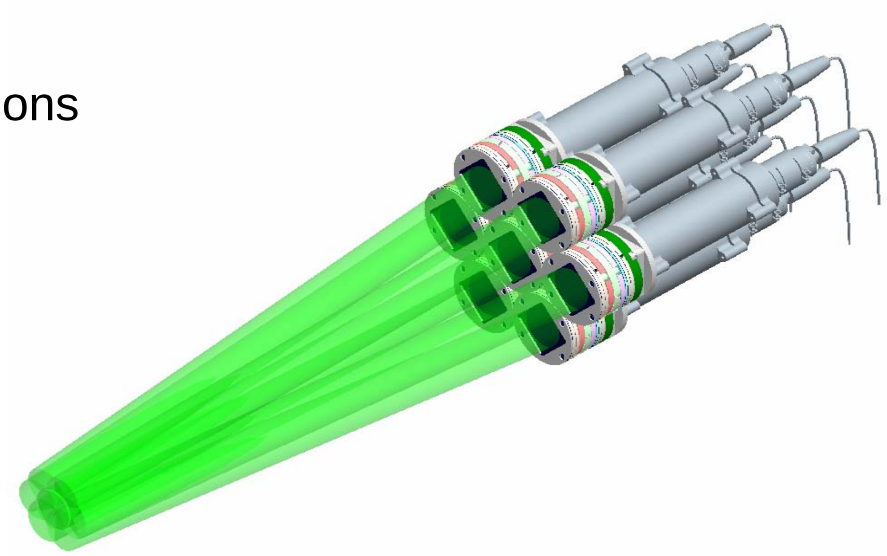


M- THEL

Summary

APPLE is a revolutionary approach to EO beam control

- **Revolutionary Architecture**
  - Coherent beam control with no moving parts
  - Distributed apertures, distributed laser train, distributed control system
  - Simple SPGD control
  - Built in compensation for aberrations
  - Modular, Adaptive, and Flexible



- **Enabling Mission Attributes**
  - Conformal
  - Scales to high powers
  - Scales to large apertures
  - Offers order-of-magnitude SWaP savings over conventional systems
  - Advantageous to a wide variety of programmable Multi-function systems